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An Integrated Research Plan for IFE Technology*

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IAEA Technical Committee Meeting on
Physics and Technology of
IFE Targets and Chambers
Madrid, Spain
7-10 June 2000

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Contributing Institutions

- **Lawrence Livermore National Lab (LLNL)**
- **General Atomics (GA)**
- **Georgia Institute of Technology (GT)**
- **Idaho National Engineering and Environmental Lab (INEEL)**
- **Los Alamos National Lab (LANL)**
- **University of California at Berkeley (UCB)**
- **University of California at Los Angeles (UCLA)**
- **University of California at San Diego (UCSD)**
- **University of Wisconsin (UW)**
- **Argonne National Lab (ANL)**
- **Sandia National Lab (SNL)**

Mission of IFE Technology Activities

Address and resolve the critical issues for high-rep-rate chamber concepts, target fabrication and injection for heavy ion and laser drivers through assessment studies, experiments and numerical simulations.

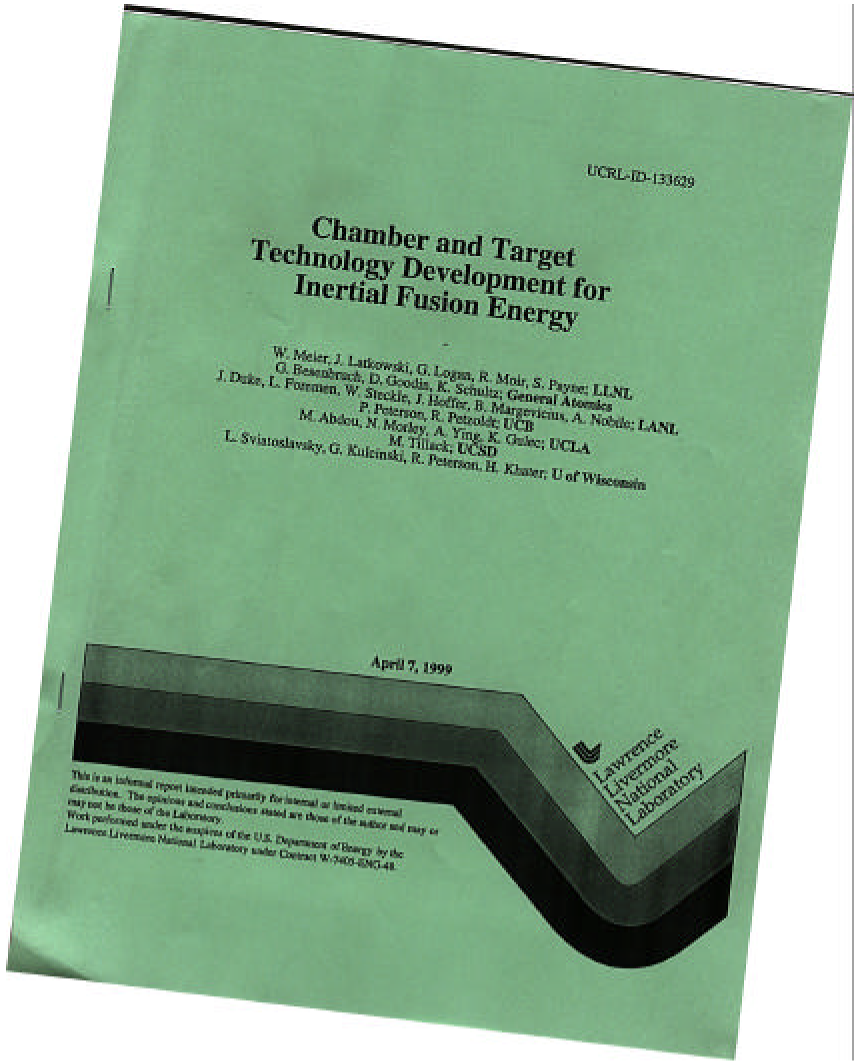
Scope of IFE Technology Activities

- **R&D planning (with driver and target physics colleagues)**
  - Development paths and facilities, e.g., IRE, ETF, Demo
- **Chamber Technologies**
  - High rep-rate operation, protection of structures
- **Chamber/driver interface**
  - Protection of final focus magnets and laser optics
- **Safety and environmental**
  - Assessments and improvements to create attractive power plants
- **Target fabrication and injection**
  - Low cost, high pulse rate systems for ion and laser drivers
- **System integration**
  - Fitting the pieces together including target designs and drivers

Summary of Key Issues

- **Chambers**
  - Thick Liquid Wall - Protective liquid blanket formation, chamber clearing between pulses
  - Dry Wall - First wall protection, chamber lifetime
- **Chamber / Driver Interface**
  - Heavy Ion Driver - Magnet array design, placement, and shielding
  - Laser Driver - Final optics design and survivability
- **Safety and Environmental**
  - Accident consequences, tritium containment, end-of-life radioactive materials processing
- **Target Fabrication and Injection**
  - Low cost, high-rate production
  - Injector accuracy and reliability, target tracking, target survival

A draft R&D plan was written in 1999 with wide community participation



UCRL-ID-133629

Chamber and Target Technology Development for Inertial Fusion Energy

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April 7, 1999

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.
Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

Thick-Liquid-Wall Chambers

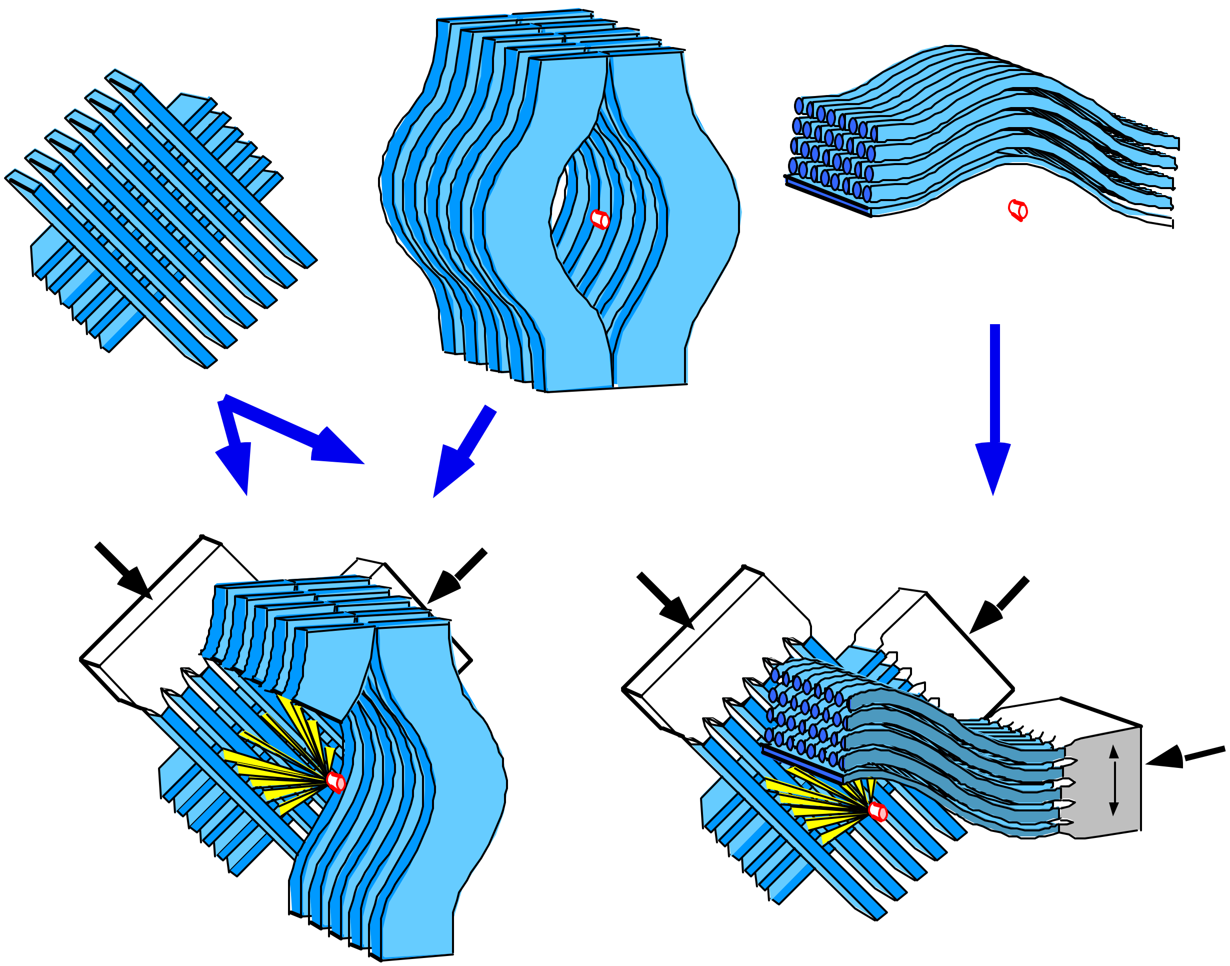
Phase-I Objective

- **Provide convincing evidence from scaled experiments and modeling that protective liquid pocket can be formed and that chamber can clear between shots**

Proposed Tasks

- **Liquid jet experiments (formation, jet quality)✓**
- **Liquid response (surface loading, bulk disruption) ✓**
- **Vaporization and Condensation ✓**
- **Incorporate new target emissions info ✓**
- **Flibe chemistry**

Pocket Configurations

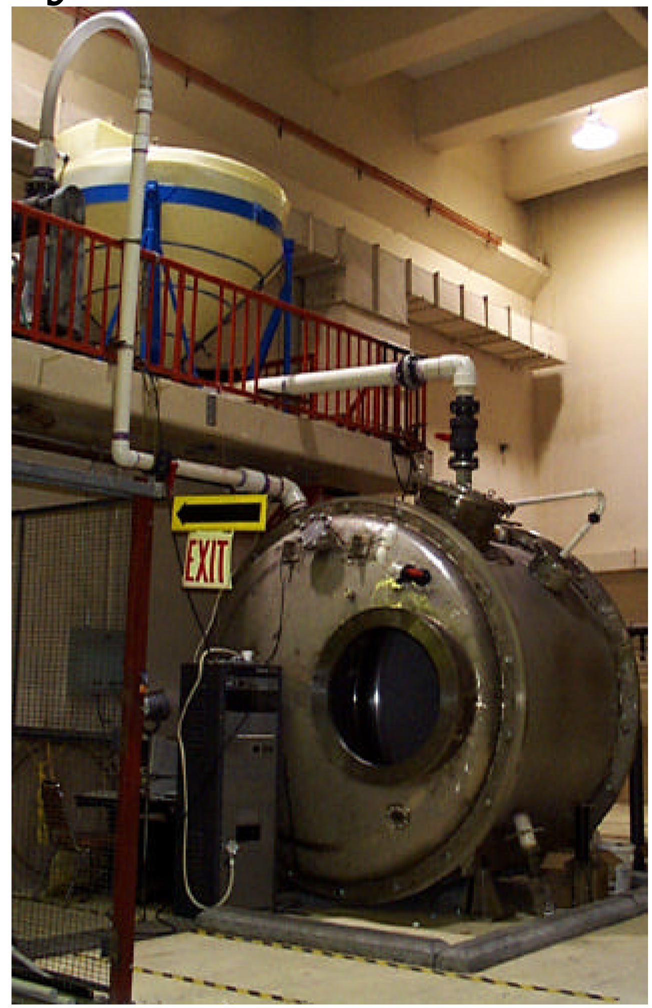


Closed Pocket　　Directed-Venting Pocket

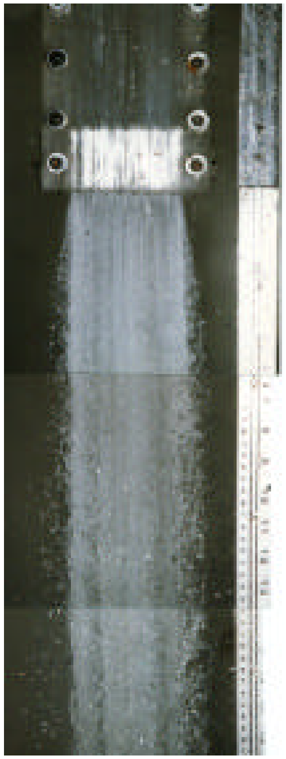
Phase-I hydraulics experiments can be performed in university-scale facilities

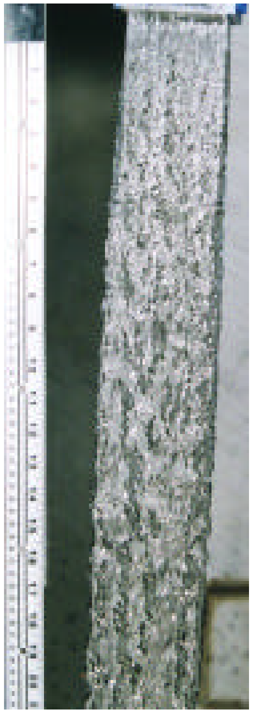
- **Example: UCB facility studies single jets and few jets (partial pockets).**
- **Transient flow into large vacuum vessel**

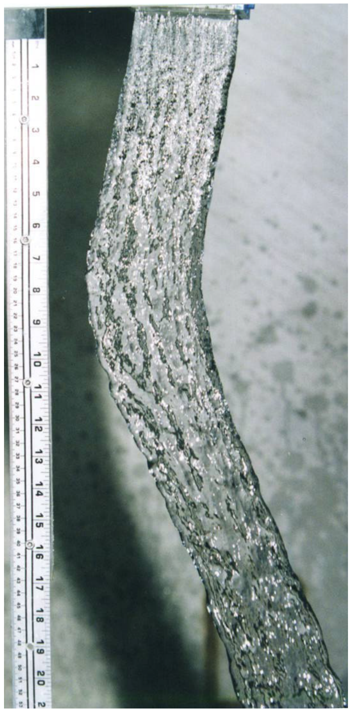
Water used to simulate Flibe (allows Re, Fr and We number matching at 1/2 to 1/4 geometric scale)



Single-jet experiments provide jet geometries for constructing integrated pockets







Bad:
Breaks up

Stationary **Oscillating**

Better: No Droplets

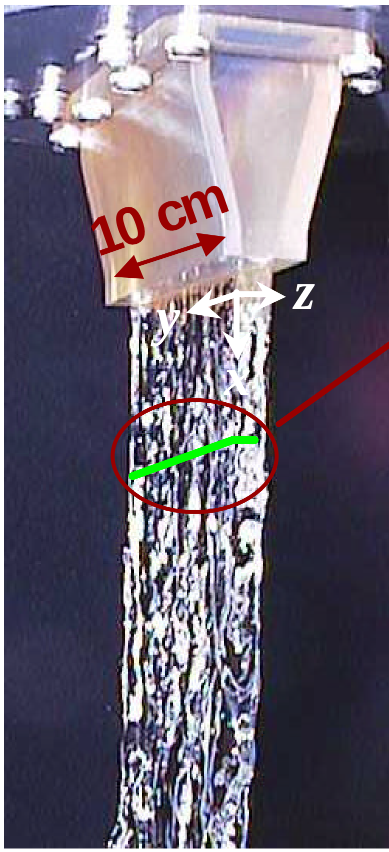
UCB Stationary Jets (1.6 cm x 8.0 cm, view from flat side, Re = 160,000, We = 29,000)

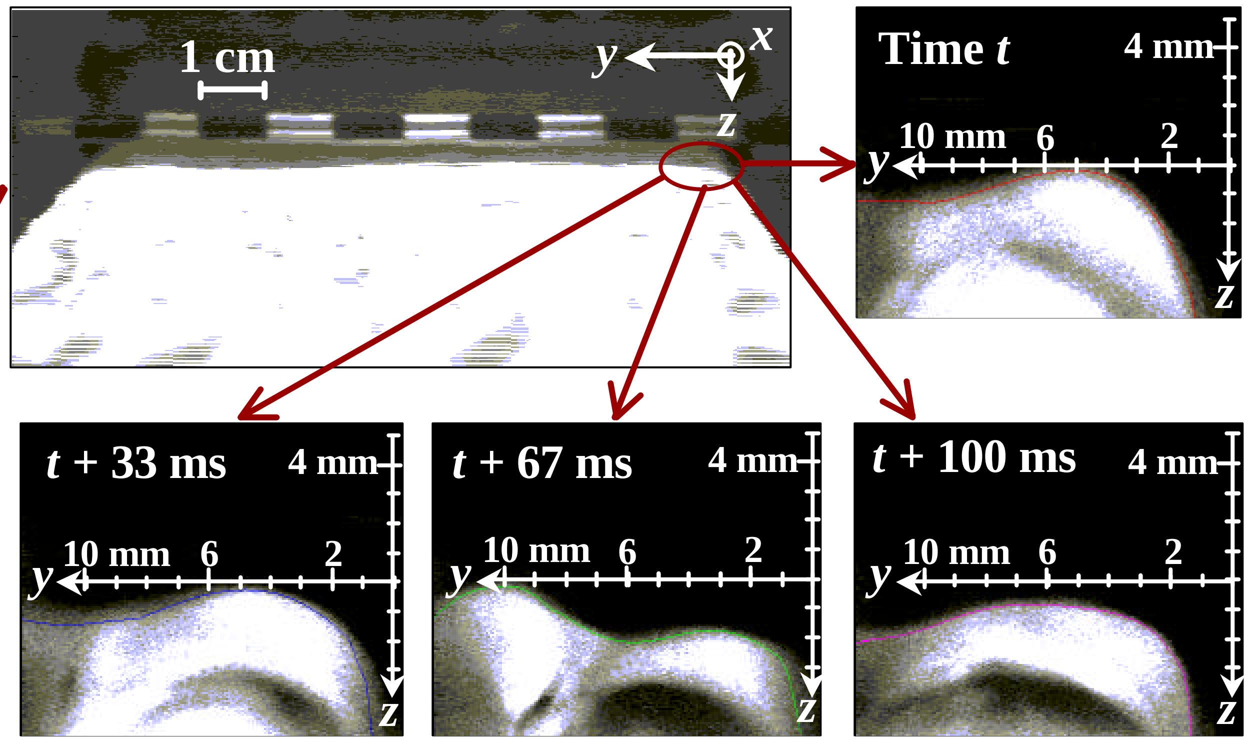
Georgia Institute of Technology

Surface Ripple in Plane Jets

J. A. Collins, D. Sadowski, M. Yoda and S. I. Abdel-Khalik

Free surface visualization: Laser-Induced Fluorescence of jet fluid (water)

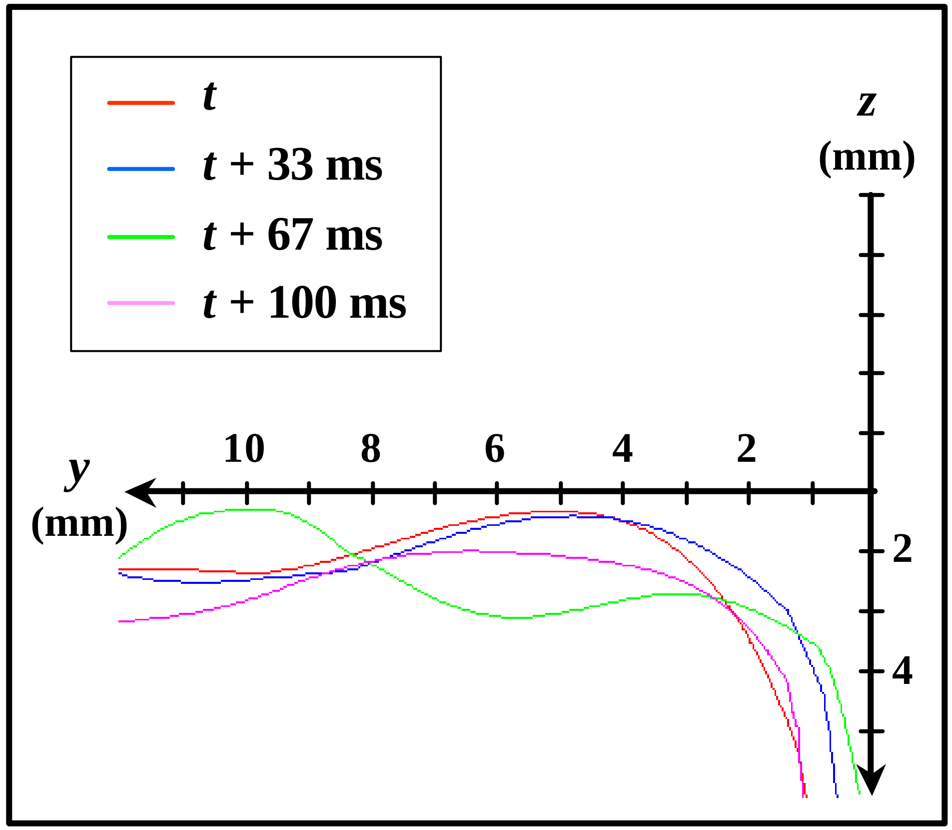




Surface Ripple in Plane Jets

Time evolution of free surface geometry

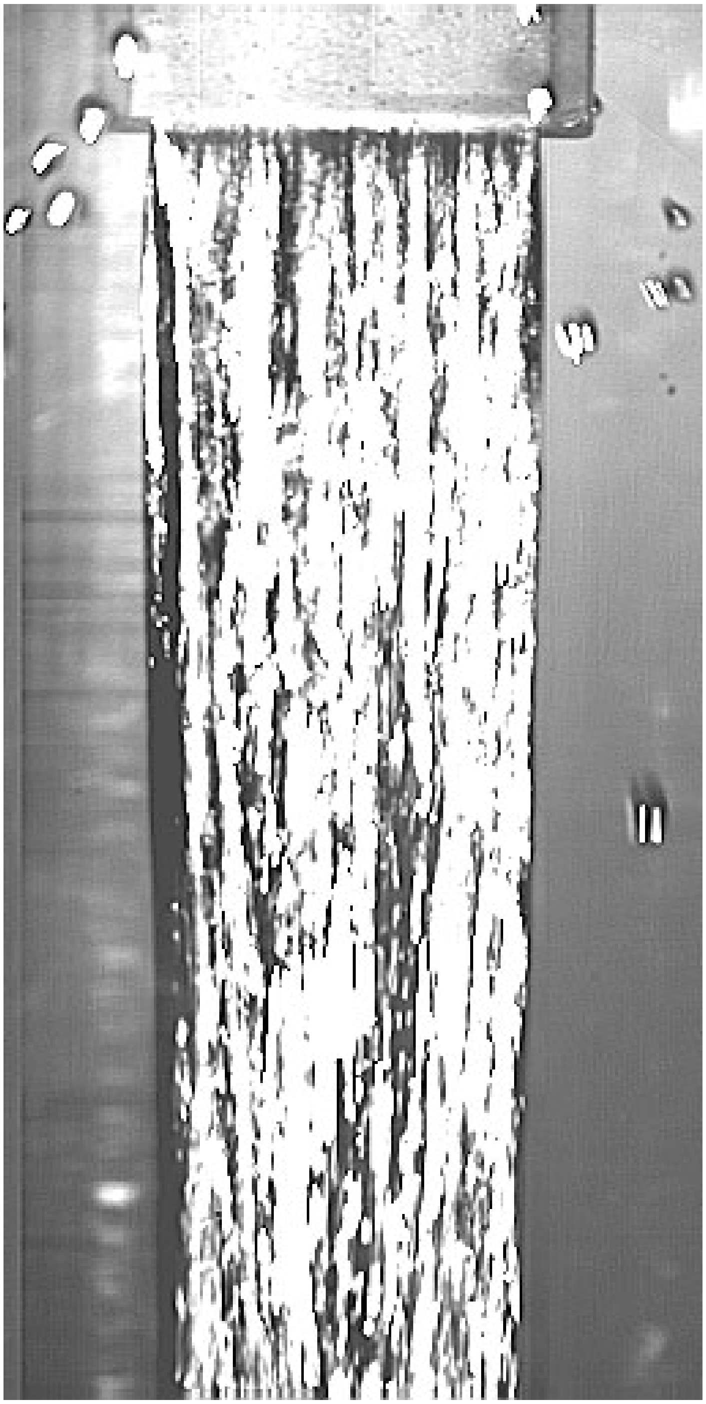
- *Re* = 3.4 ´ 10^4
- Free surface geometry 15 cm from nozzle exit (center of HYLIFE-II pocket)

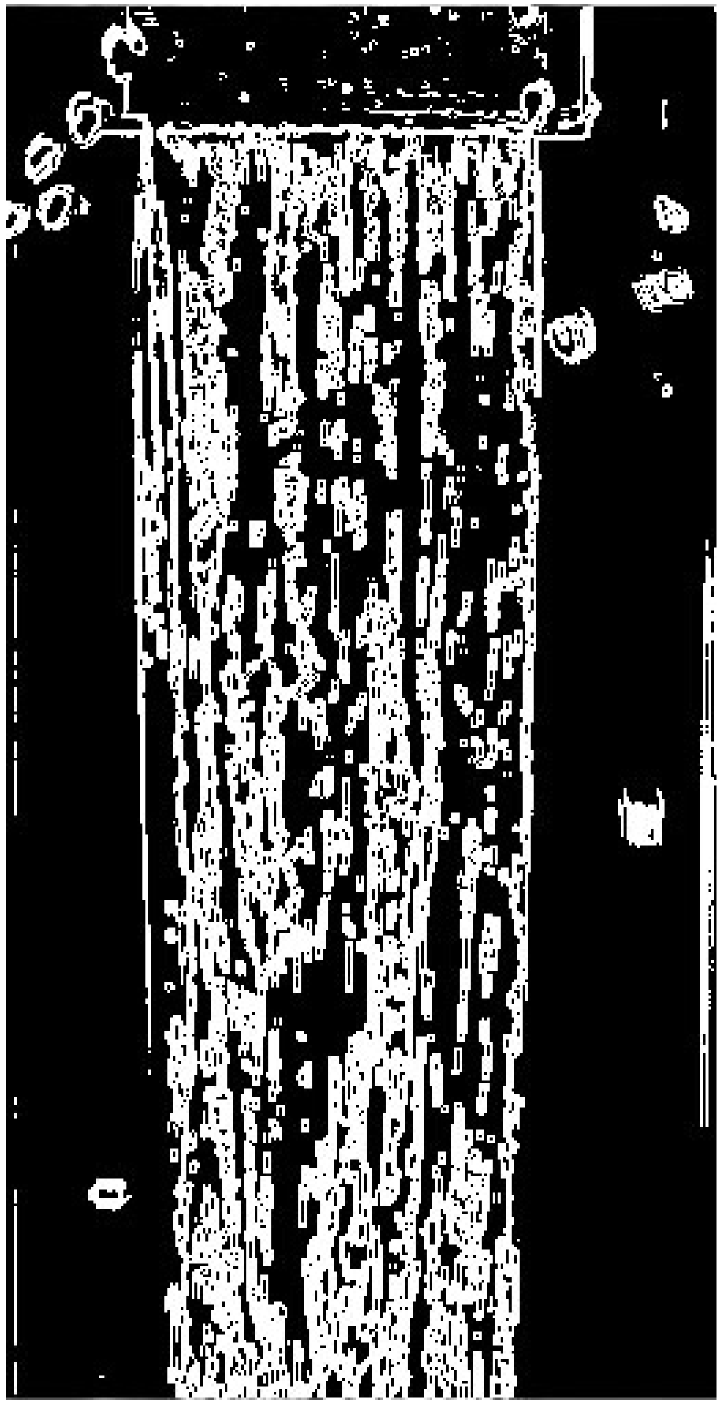


Max. instantaneous surface ripple ~2 mm at jet corners

Large variations over tens of msec

NAS2 view from flat side

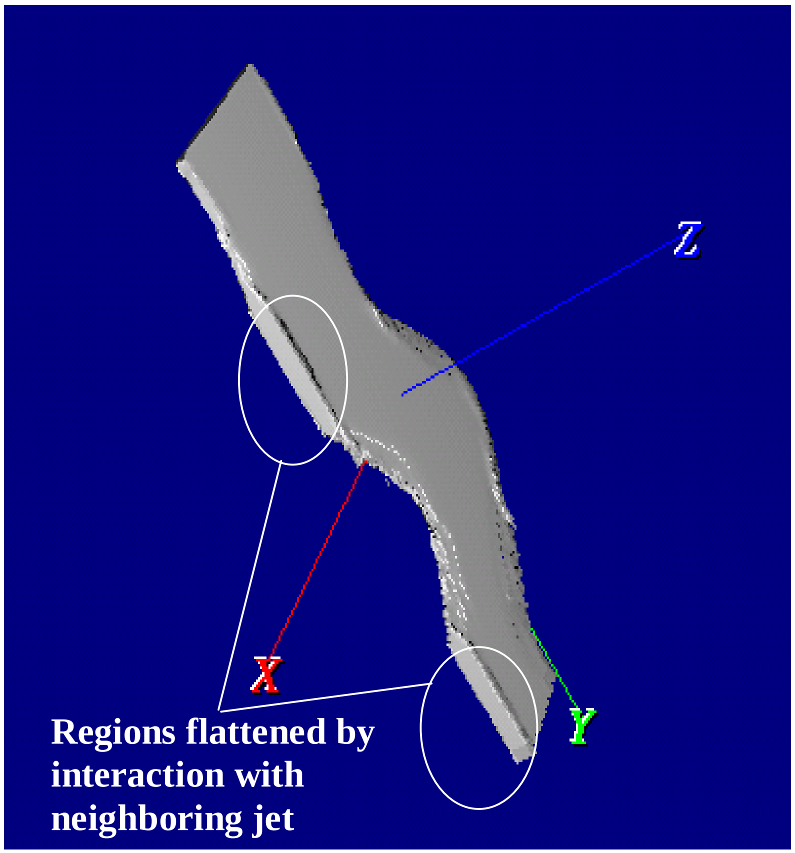




Surface structures are 0.5 to 1.5 mm in width
V = 7 m/s, Pictured Length 6 cm

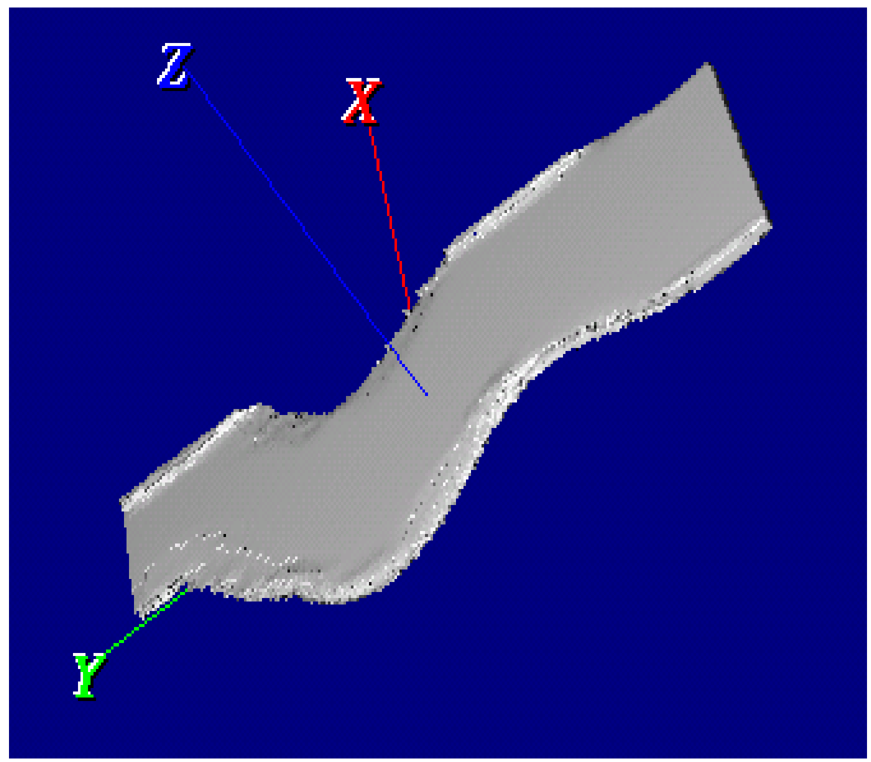
Free Surface Liquid Flow Modeling:

3D Simulation of Oscillating HYLIFE-II Jet

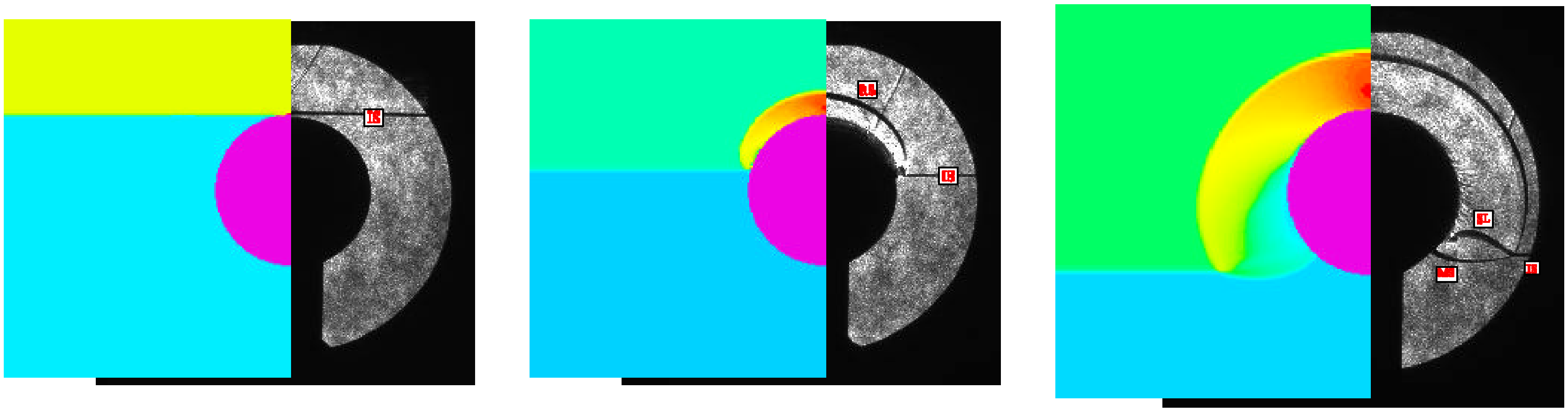


Oscillation velocity parallel to free surface plane

- Jet trajectory and pocket shape are consistent with HYLIFE design requirements
- Inter-jet spacing seals at pocket top and bottom due to interaction with "mirror" jets



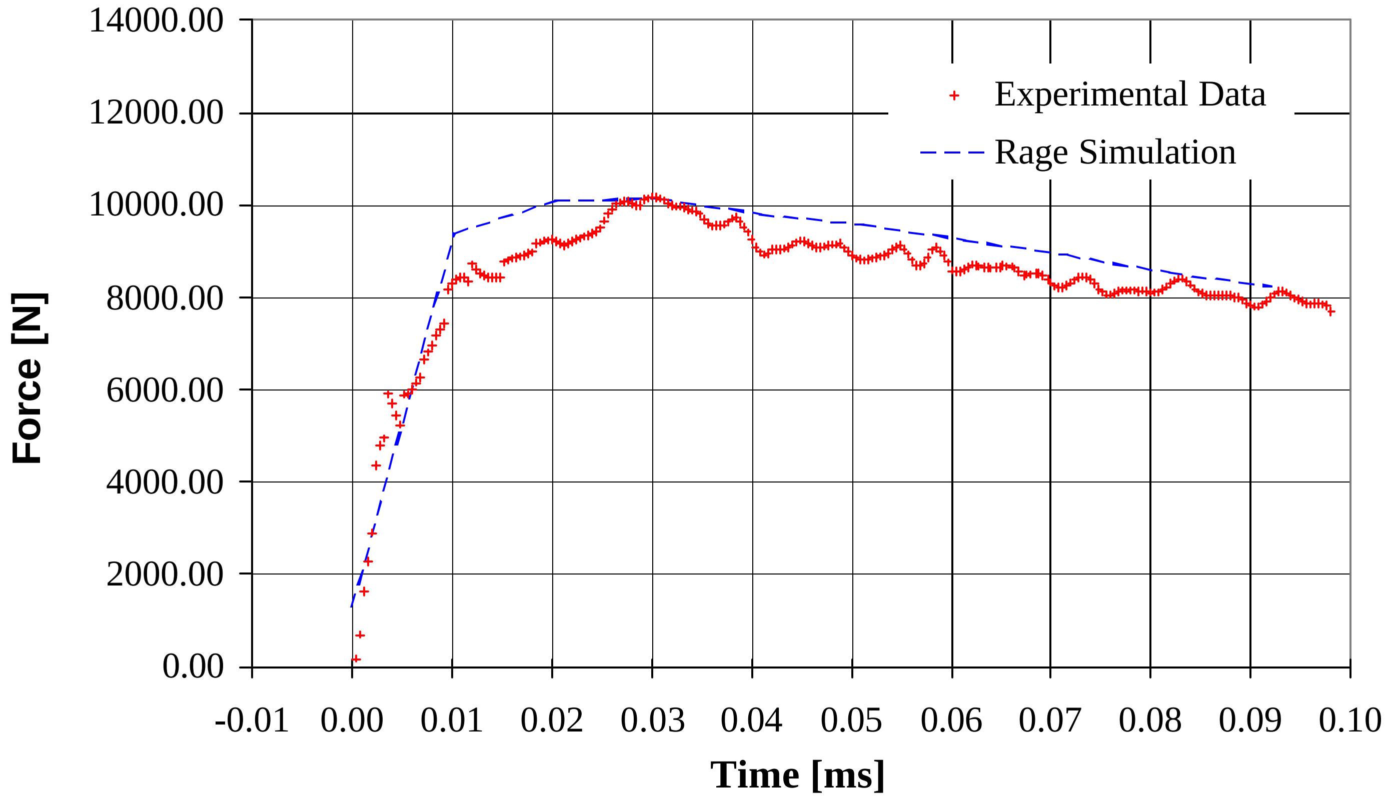
Gross Features of RAGE Simulations of Flow Around Cylinder Agree with Experiment



Density contour plots from the numerical simulation using RAGE compared to the experimental shadowgraphs. The times of the numerical simulations are t=0, t=0.03 and t=0.08 ms after a 1.85 Mach shock makes contact with the cylinder. The experimental images were taken at a time of t=0, t=0.05 and t=0.09 ms respectively.

RAGE Simulations of R-M Unstable Interface Experiments

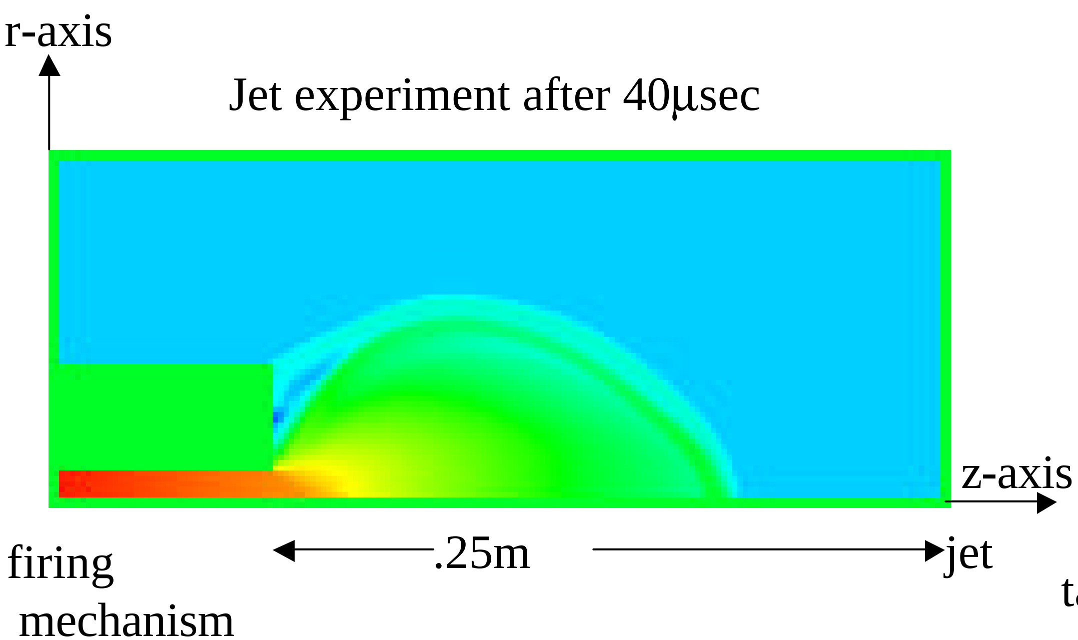
Force on the Cylinder as a Function of Time

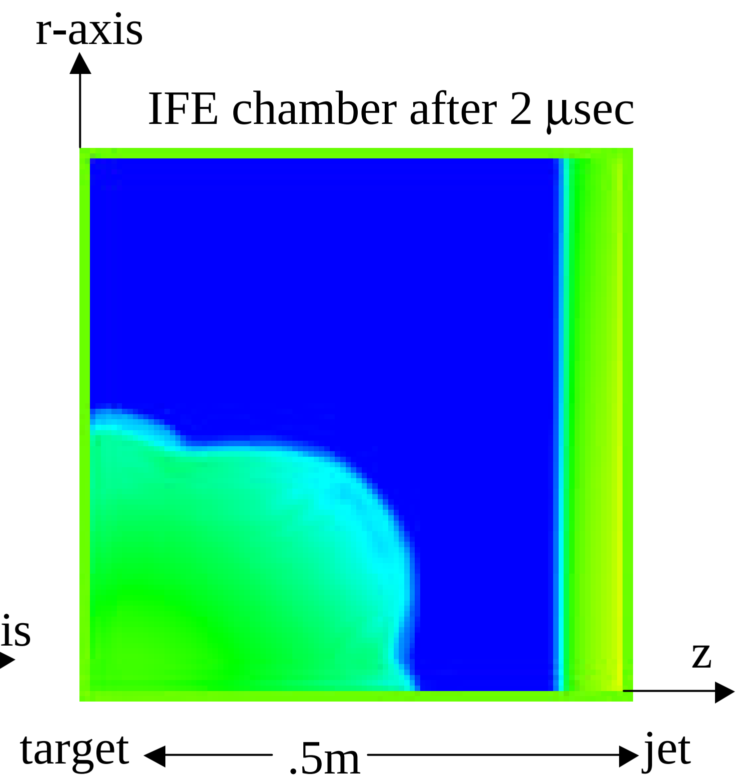


Density Contours of Jet Experiment and IFE Chamber

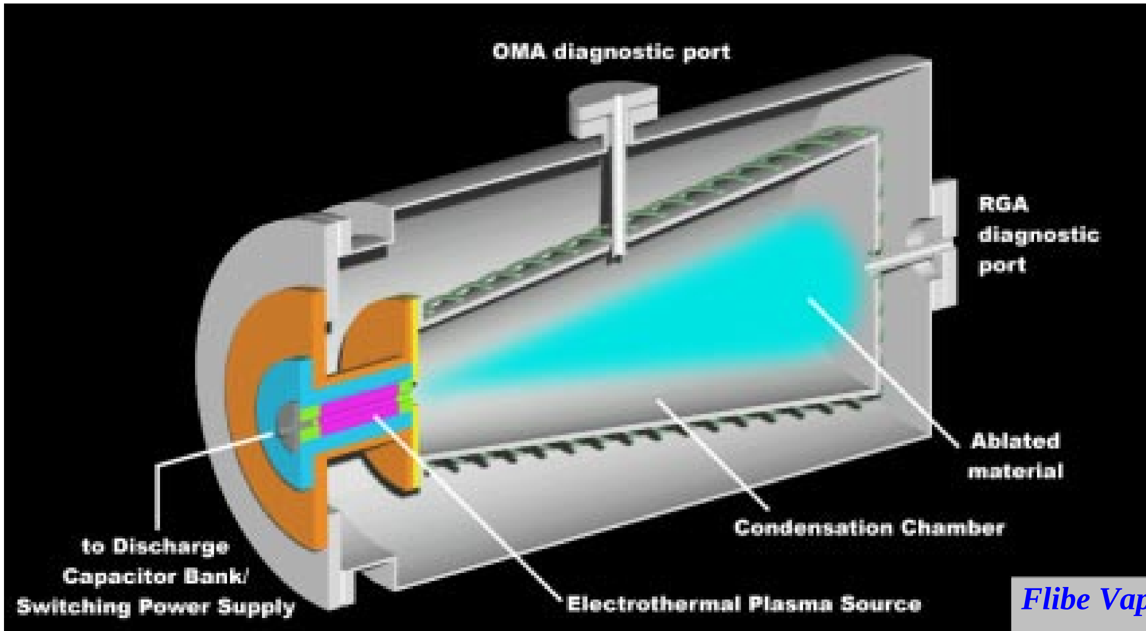
Profiles demonstrate jetting of ignition products from firing mechanism and more uniform expansion of target

Ablated jet material causes instantaneous density/pressure rise in IFE chamber





Vapor Clearing Rates for IFE Liquid Chambers

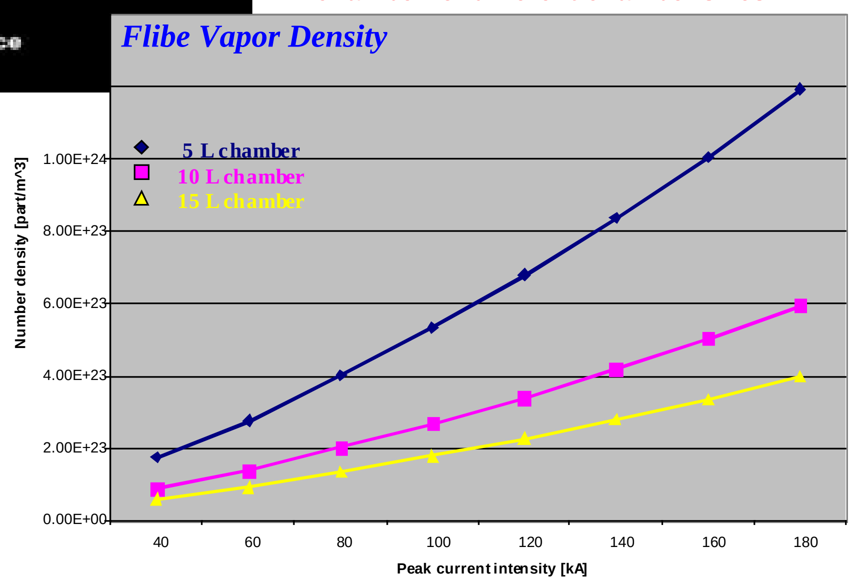


Tube-shaped Flibe plasma source

- ***Partially Ionized, high density low temperature (~ 4eV) Flibe Plasma* can be formed by the *Ablation* of a Flibe Liner with a large current discharge**

- ***A HYLIFE prototypical Flibe vapor density of 10^{18} /cc can be formed in a chamber size of about 5 liters using a discharge current of 160 kA***

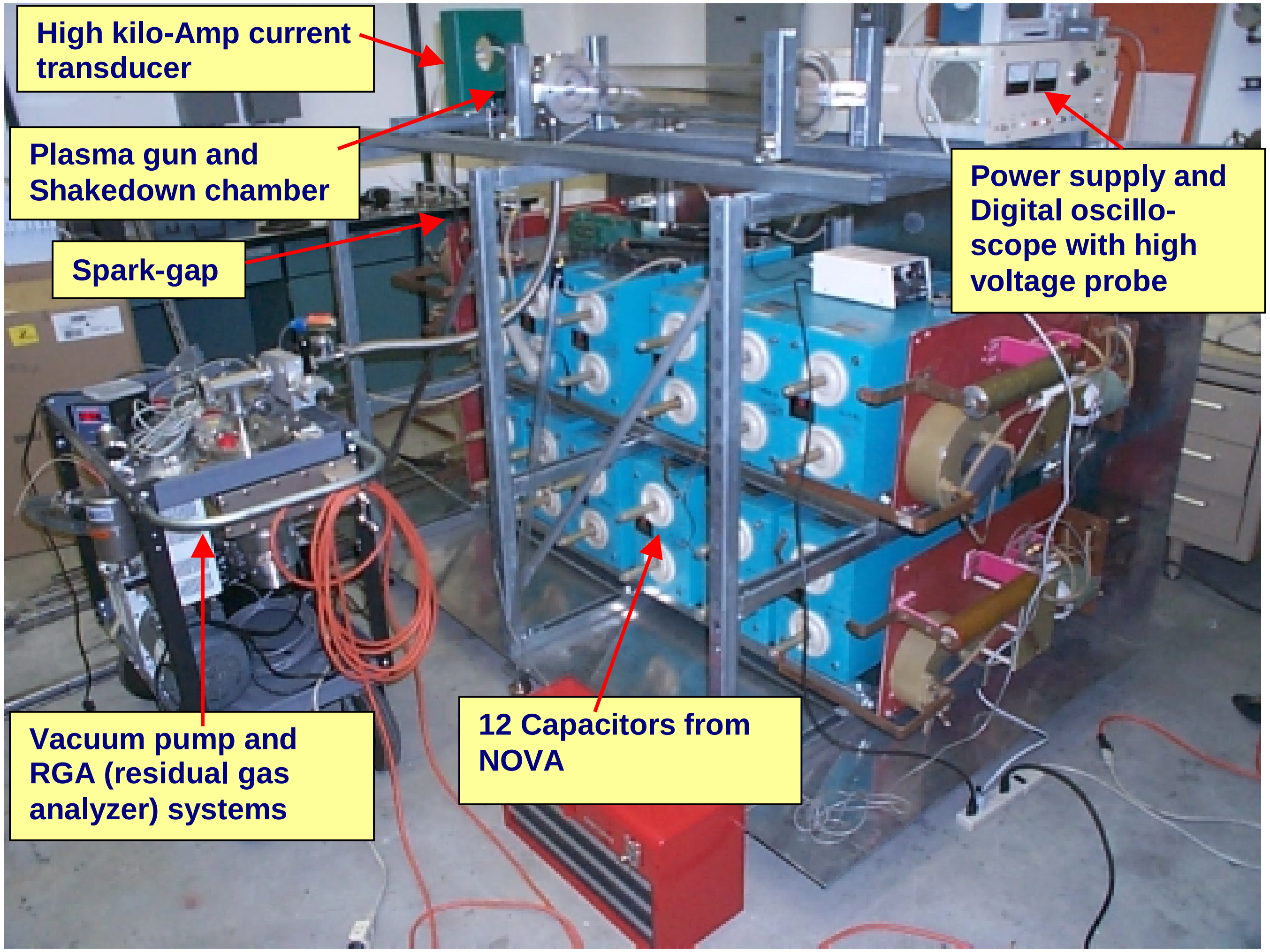
Expected number of density in the expansion chamber for different chamber sizes



Feasibility Exploration of Vapor Clearing Rates for IFE Liquid Chambers

Principal FY1999/2000 Achievements:

- Constructed a pulsed electro-thermal plasma launcher (a pulsed energy source that simulates IFE pellet explosion for rapid Flibe vapor generation) using 12 capacitors received from NOVA laser at LLNL.
- Shakedown tests at 5 kV and 50 μF (one capacitor) have ablated some amount of Lexan (to be quantified). Total maximum energy capacity = 120 kJ.
- Flibe casting into a cylinder tube (as for ablation) is under evaluation.



Dry-Wall-Chambers

Phase-I Objective

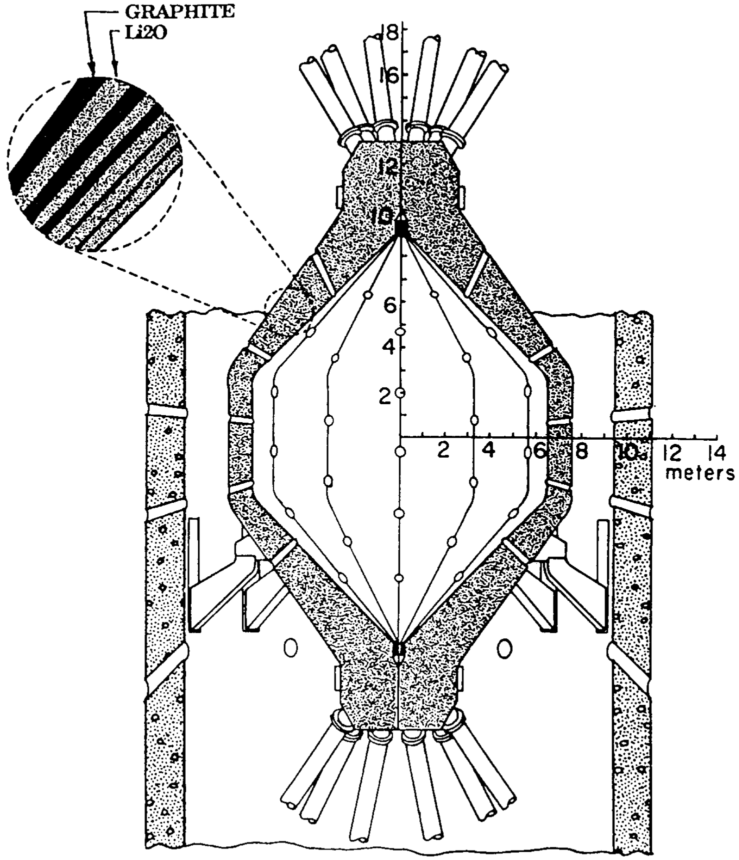
- Develop design that is more tolerant of uncertainties in material lifetime and evidence supporting wall life > 1 year

Proposed Tasks

- Radiation damage data assessment & update ✓
- Incorporate new target emissions info ✓
- Chamber dynamics modeling ✓
- Chamber dynamics experiments
- Granular erosion tests

Sombrero is an example Dry Wall chamber

- **Example: Sombrero Conceptual Design**
  - Direct drive targets
  - Carbon-carbon first wall and flow structures
  - 0.5 Torr xenon gas controls x-ray and debris damage to first wall

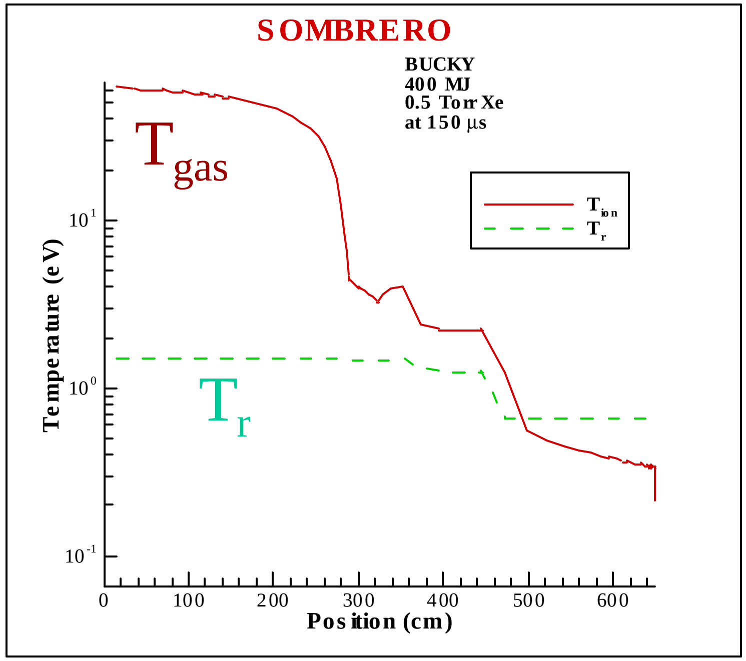


Understanding of Dry-Wall Target Chambers for IFE (SOMBRERO) (supported by NRL)

- Target output dominated by debris ion emission: 1.65 MeV C in SOMBRERO.
- Gas radiation-hydrodynamics sensitivity to gas atomic properties studied: in 0.5 Torr Xe (SOMBRERO) first wall conditions are a strong function of Planck opacity.
- Wall erosion due to thermal evaporation studied for SOMBRERO conditions versus graphite thermal conductivity: 115 W/m-K (at temperature) or better is required.
- Thermal conductivity of graphite: experimental data shows reduced neutron damage effect at expected (SOMBRERO) irradiation temperatures, 115 W/m-K should be achievable.
- Target heating during injection severe on bare ablator cryogenic fuel targets for heating limits imposed by present target fabrication technologies (0.5 K temperature rise).
- Proposal to OFES has been made to experimentally and computationally study these issues further.

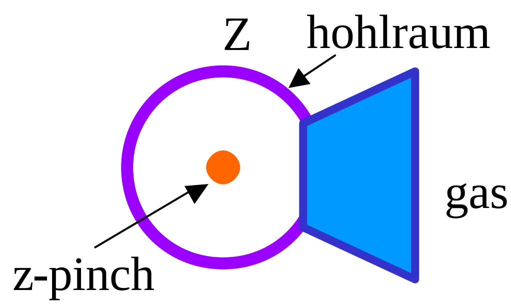
Radiation Transport in Gas Protected Target Chambers

Issue: Radiation Transport in SOMBRERO fireballs is far out of equilibrium and flux-limited radiation diffusion must be validated.

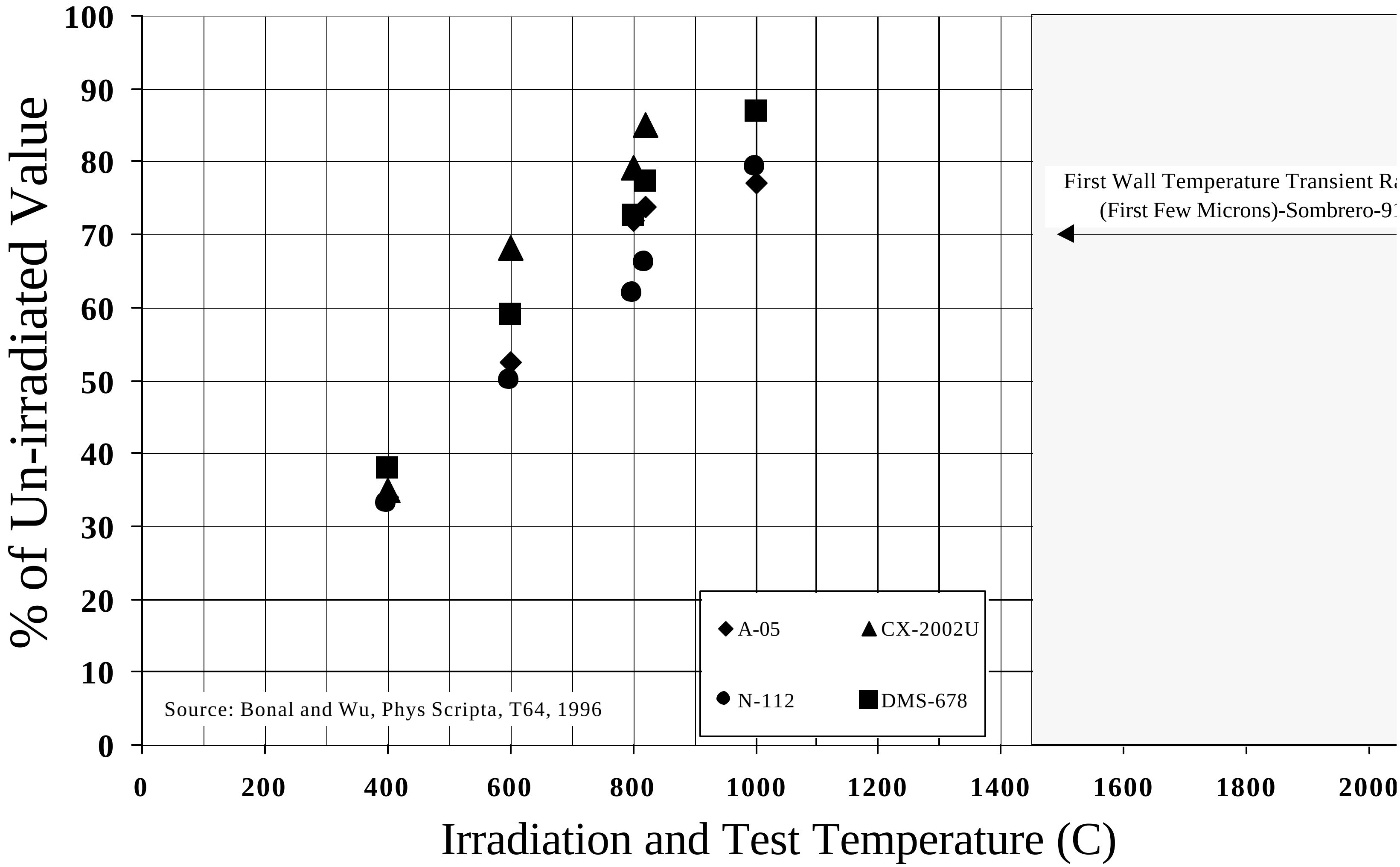


Status: Radiation-hydro codes (BUCKY, RAGE, Lasnex) can model radiation-dominated-blasts. NRL laser generated blasts in the 80's showed that radiation fronts can be unstable.

Needs: High energy density (enough to heat Xe to ~ 100 eV) experiments on Z would simulate radiation dominated blasts. Need a sample large enough to be optically thick.



Neutron Irradiated Thermal Conductivity of Graphite at » 1-2 dpa Approaches Un-irradiated Thermal Values at High Temperatures



Heavy Ion Driver / Chamber Interface

Phase-I Objective

- Develop final focus magnet designs consistent with shielding and illumination geometry required by target design.

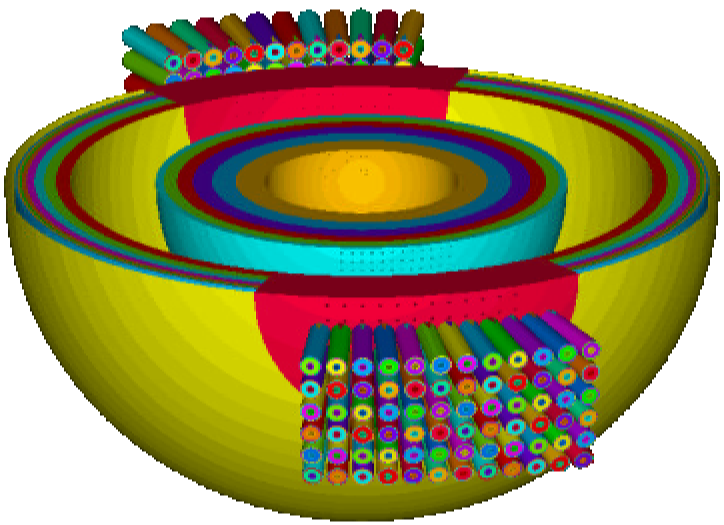
Proposed Tasks

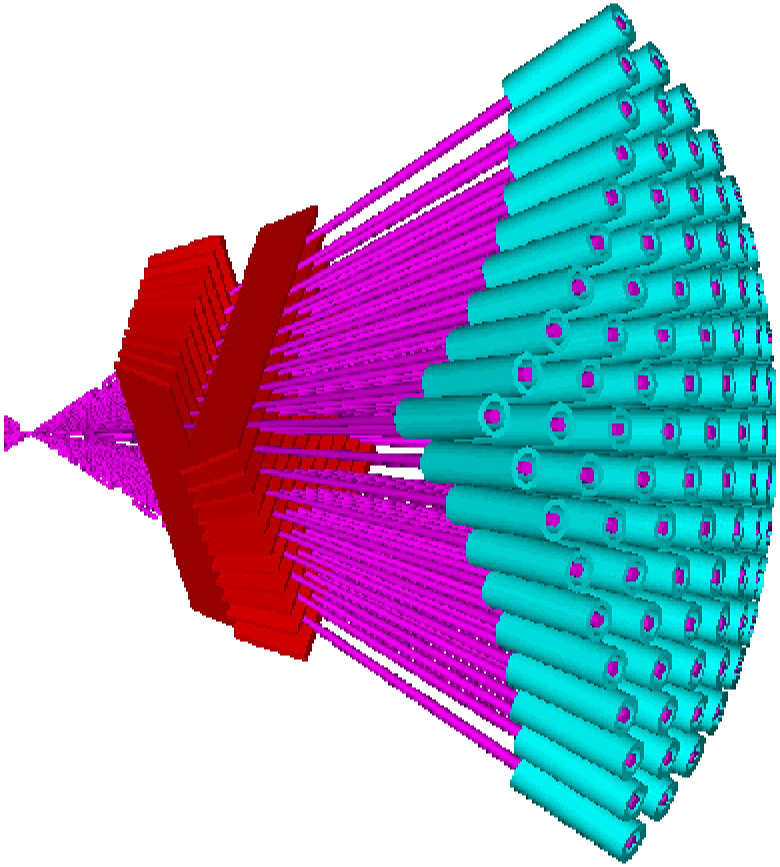
- Magnet array layout based on beam physics ✓
- Magnet shielding design ✓
- Integration with fluid chamber design ✓

We are working towards a self-consistent design for the driver/chamber interface

- **Realistic, 3-D models are being used to analyze the driver/chamber interface:**

- To study S&E issues related to final focus design





- To determine the importance of precision Flibe jets

Laser Driver / Chamber Interface

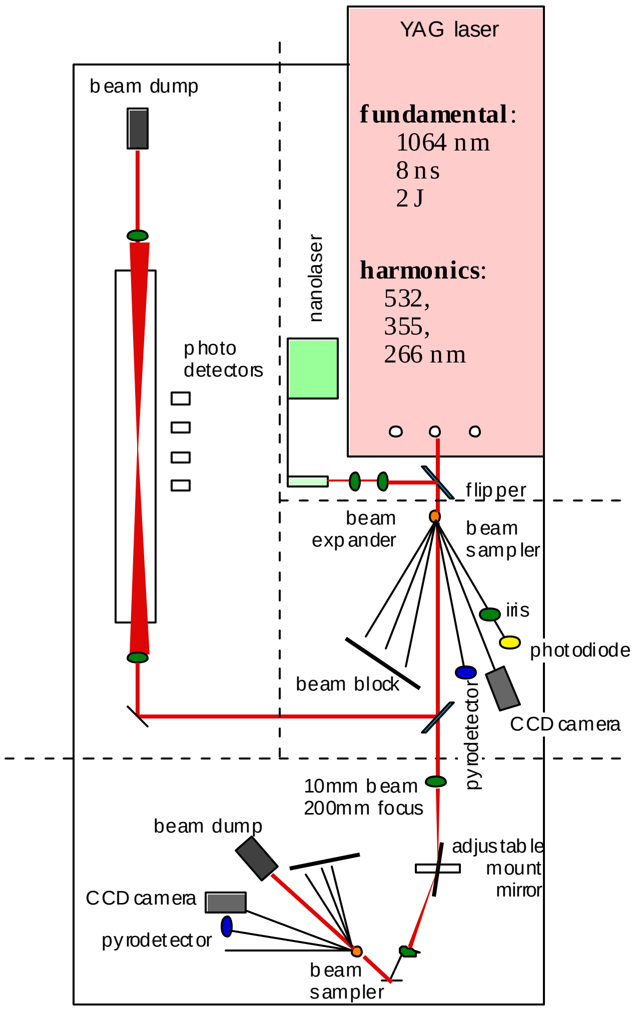
Phase-I Objective

- Design concepts and convincing evidence (from experimental data and modeling) that laser final optics (e.g., grazing incident mirrors and hot fused silica) will survive > 1 year

Proposed Tasks

- Experiments and modeling of laser damage to GIMM ✓
- Experiments with grazing incidence liquid metal mirrors
- Radiation damage experiments and modeling ✓
- Gas protection / shock tube experiments

Laser-Material Interaction Experimental Plan



Final Optics Damage and Protection:

- Damage limits on GIMMs
- Impurity effects on final optics
- Beam quality from liquid mirrors
- Advanced protection concepts

Beam Propagation Physics:

- Beam degradation near/ beyond breakdown
- Effect of background medium

Principal Diagnostics Under Development:

- Beam profile
- Shack-Hartmann wavefront sensor
- Pyroelectric detector
- Fast photodiodes
- Post-test microscopy

UC San Diego Laser Test Facility

Fundamental:
2 J, 8 ns
1.06 μm

Harmonics:
0.532 μm
0.355 μm
0.266 μm

YAG laser inside cleanroom enclosure (power supply at left)

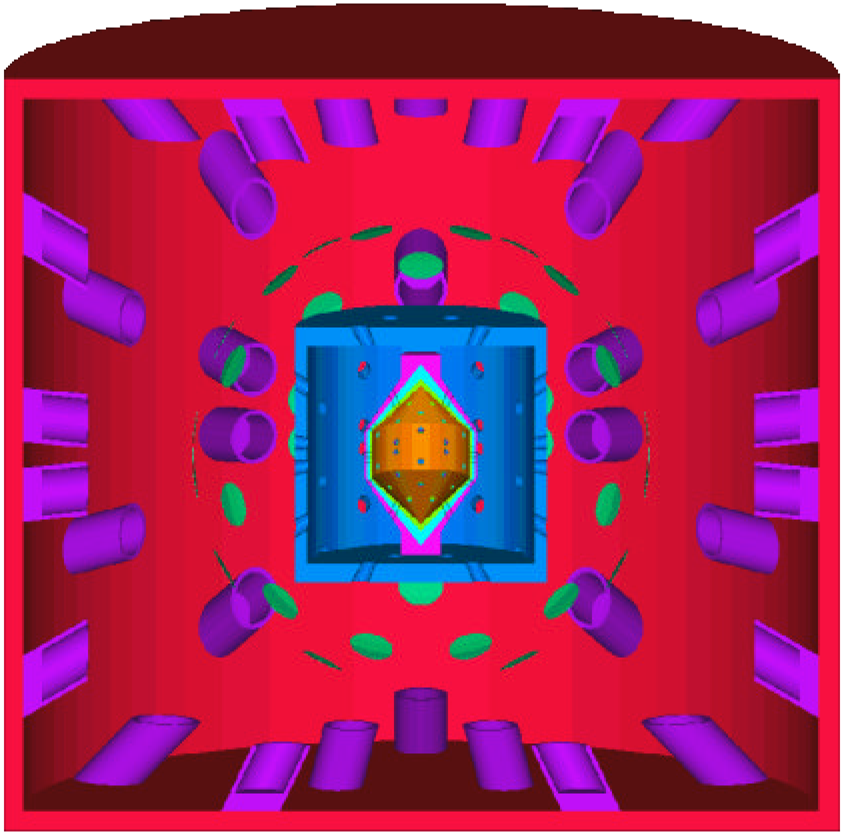
Radiation damage issues for Laser-IFE designs are being addressed

- Detailed 3-D models are being developed for S&E and radiation damage analyses

- By using neutron dumps (violet), the fast neutron flux in the focusing optics (located outside of dumps) is reduced by ~ 4×

- Previous 1-D work significantly underestimated the neutron fluence at the focusing optic due to a significant contribution from scattering in the final optic

Model of a DPSSL-modified SOMBRERO target building includes final optics and neutron dumps



Safety and Environmental

Phase-I Objective

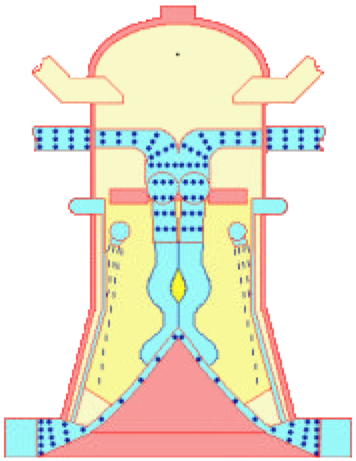
- Power plant designs with < 1 rem dose at site boundary consistent with measured release fractions for key radioactive isotopes.

Proposed Tasks

- Accident analyses and resulting doses ✓
- Experiments to measure release fractions for key isotopes ✓
- Evaluation of end-of-life material processing trade-offs (recycle versus disposal, volume versus hazard potential) ✓
- Dust / Aerosol transport experiments

We have completed a loss of coolant/breach of confinement analysis for HYLIFE-II

- **Upgraded state-of-the-art codes and methodologies have been used to perform an accident analysis for HYLIFE-II IFE power plant design**
- **Modeled a complete loss-of-coolant accident, with simultaneous break of all beam tubes and failure of the containment building wall**
- **Thermal-hydraulics, heat transfer, aerosol physics, and fusion product release and transport calculations have been made**
- **According to the Fusion Safety Standards, a site boundary (1 km) accident dose of 10 mSv (1 rem) triggers the requirement for an evacuation plan**



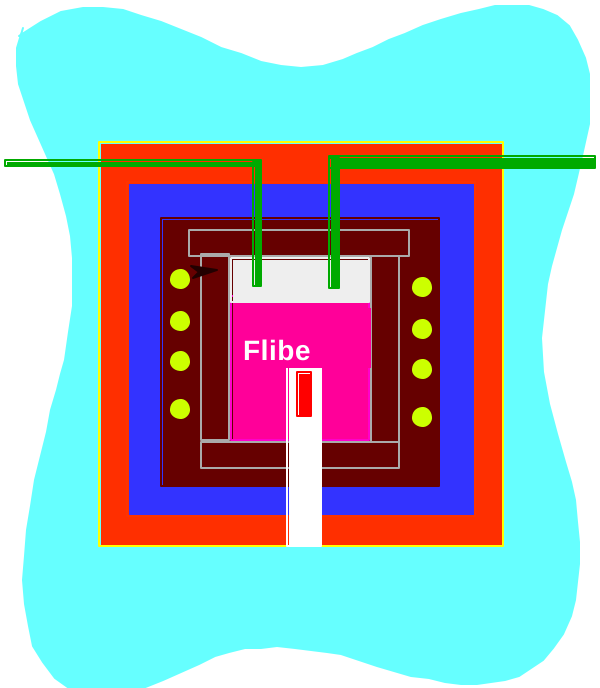
HYLIFE-II

Radioactive source	Mobilized mass/activity	Release fraction	Dose at site boundary
SS304 corrosion/ oxidation products	0.5 kg / 1.31×10^{12} Bq	11%	43 mSv / 4.3 mrem
Vaporized Flibe	10 kg / 7.06×10^{15} Bq	12%	564 mSv / 56.4 mrem
HTO trapped in steel structures	1 kg / 4.99×10^{16} Bq	50%	5.34 mSv / 534 mrem

Site boundary dose of 6 mSv (0.6 rem) implies that an evacuation plan would not be needed

Fusion Safety Program Support of IFE Technology

FLIQURE



Objectives

- Neutron irradiation by Cf-252 source
- Be and T compound and aerosols mobilized during air or steam ingress
- Tritium permeation through metal surface
- In FY-00, engineering design. Construction and operation in FY-01

Safety Model Development

- Incorporate Flibe properties into safety codes (ATHENA, MELCOR)
- Support IFE/LLNL colleagues in use of fusion safety codes MELCOR and CHEMCON

Target Fabrication and Injection

Phase-I Objective

- Demonstrate that a credible pathway exists for low cost target fabrication and accurate injection without damage to targets.

Proposed Tasks

- Target material/component development ✓
- Identification and development of processes that scale to high production rate ✓
- Injector design, assembly and experiments ✓
- Experiments on target thermal response
- Experiments on target mechanical response

CREDIBLE TARGET FABRICATION AND INJECTION ARE NEEDED FOR IFE

- **Design studies show plausible manufacturing and injection processes and reasonable costs**
- **We must demonstrate:**
  - Technical feasibility of approaches
  - Accuracy can meet requirements
  - Survival of targets during injection
  - Reliability of providing ~5 targets/second, 24 hours a day, >300 days/year
  - Low cost of production — including labor, capital, materials and disposal
- **We have now begun to address these issues**
  - Need to show a credible pathway to IFE exists during Phase I, before investing in the IRE

Design Studies:	
Target factory costs	\$50–90M
Unit cost	20–30¢/target

Typical Specifications

Capsule out-of-round	$\leq$0.1%
Ablator thickness	$\leq$1%
Outer surface smoothness	$\leq$200 Å
Inner surface smoothness	$\leq$1 μm
Capsule centered in hohlraum	$\leq$25 μm
Allowed ΔT after layering	$\leq$0.5 K
Location at shot time (indirect)	$\pm$200 μm
(direct)	$\pm$20 μm
Reliability	$\geq$99%

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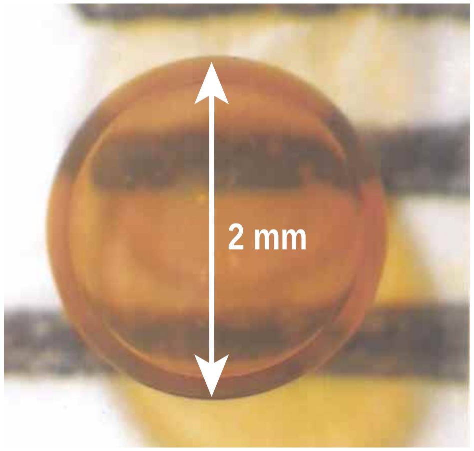
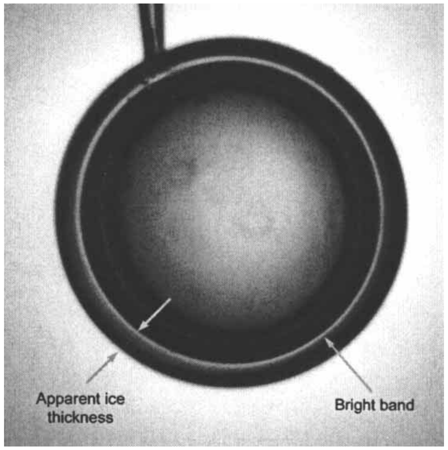
GENERAL ATOMICS

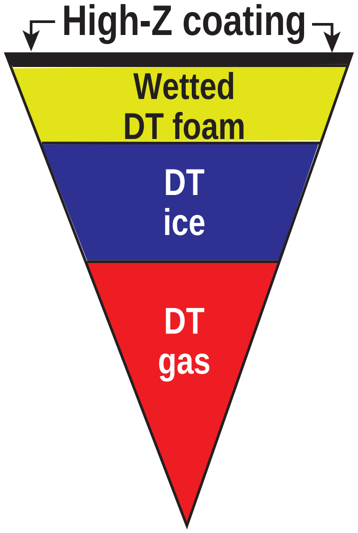
IFE CAN BUILD UPON ICF TARGET FABRICATION TECHNIQUES



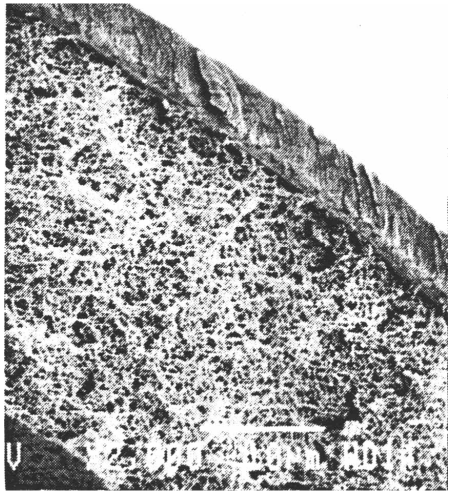
Foam Shells



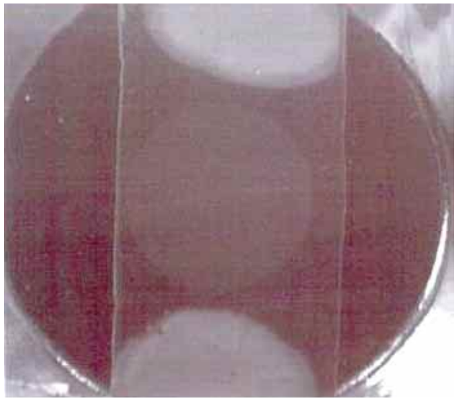
DT Ice Layer



Radiative Preheat
Direct Drive IFE Target Design



Overcoated Foam



Metal on Foam

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GENERAL ATOMICS

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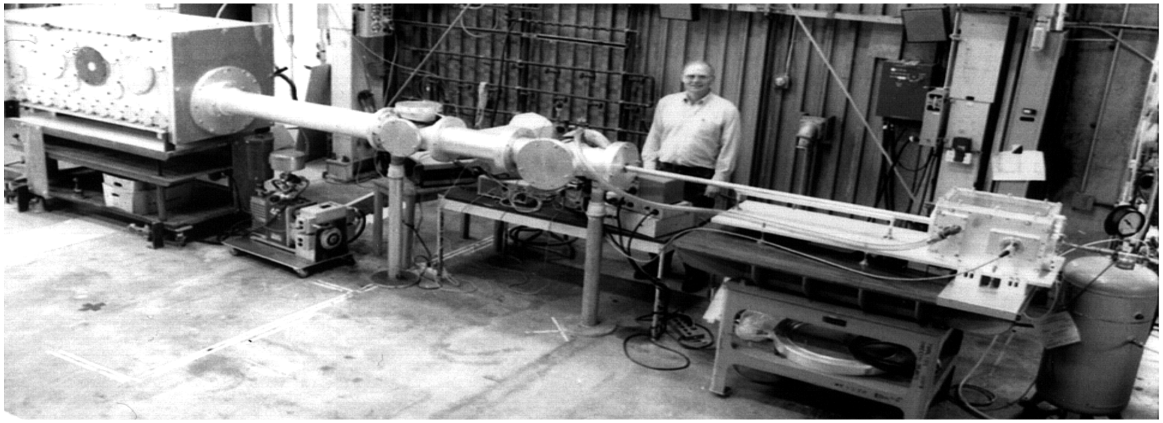
PREVIOUS EXPERIMENTS SHOW PROMISING RESULTS FOR TARGET INJECTION

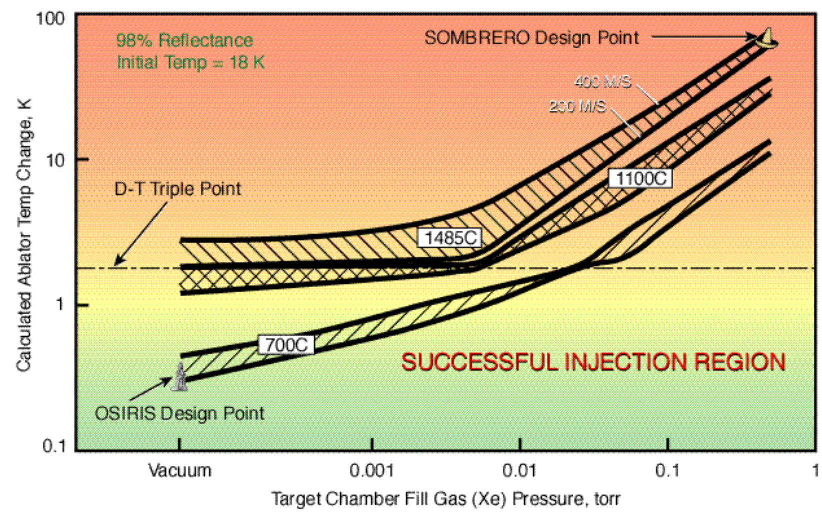
- Gas gun experiments at LBNL have demonstrated the indirect drive requirements can be reliably achieved at room temperature and low rep rate
- Preliminary experiments with surrogate direct drive targets in vacuum at room temperature and V≅100 m/s also met indirect drive accuracy specs
- Even for high reflectivity targets, direct drive may require development of thermal protection schemes and/or high speed injection and tracking methodologies



IFE Target Injection Experiment at LBNL

DESIGN OF EQUIPMENT FOR DEMONSTRATION OF IFE TARGET INJECTION AND TRACKING IS UNDERWAY

- Prepared Detailed Injection & Tracking Experimental Plan in FY99 (GA-C23241)
  - Document includes both a Technical Plan and a Program Plan (cost and schedules)
- Gas gun is selected as experimental injector
  - capability to meet requirements at lowest cost
  - demonstrated technology with minimum development
  - primary goal is to acquire target data – not develop advanced injection systems
- Continue evaluation of electromagnetic systems for future applications
  - Advantages include non-contacting injection and no propellant gas
  - Depends upon availability of higher current density superconductors
- Design of experimental target injection and tracking system is progressing well
  - Draft system requirements (12/99)
  - Conduct CDR meeting (9/00)
  - Design strategy = highly modular system layout applicable to both direct and indirect drive targets
- Related issues are being addressed
  - Developing scientific basis for successful target injection
  - Target heating during injection subject of recent master's thesis
  - Target fabrication interfaces
  - Coordination of target-related activities (workshops)



GENERAL ATOMICS

Summary

- IFE technology R&D plans have been drafted and will continue to evolve
- Current R&D activities in chamber and target technologies focus on addressing key feasibility issues
- Work includes both small scale experiments and modeling by national labs, universities and industry
- Current R&D will prepare for decision to proceed with Integrated Research Experiment(s)